Automated Fault Detection and Diagnostics for Vapor Compression Cooling Equipment

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The Need for Low-Cost Solutions

Automated fault detection and diagnostic (FDD) systems have the potential to reduce equipment downtime, service costs, and utility costs. However, very few commercial products exist and the ones that do exist are very specialized. This may be surprising to some, considering that FDD is very well developed for other applications such as for nuclear power plants, aircraft, chemical process plants, and to a lesser extent automobiles. However, the benefits of FDD for HVAC&R systems are lower than for critical applications such as nuclear power plants or aircraft or for production facilities such as chemical process plants.

For any application, the benefits of FDD can be divided into two general categories: improved safety and reduced cost to operate. For the nuclear power or aircraft industries, safety is an overriding consideration and expensive sensors and electronics can be used within FDD systems to achieve this goal. In a chemical process plant, the output of the plant is a product and equipment failures and inefficiencies can have a significant impact on the product costs. In this case, automated FDD systems can go along way towards reducing downtime and improving production efficiencies.

FDD systems are generally not necessary to ensure safety in HVAC&R applications. Therefore, the benefits must be derived from reduced operating costs. FDD applied to an HVAC system that serves a commercial building could reduce operating costs by lowering service and utility costs, and improving business productivity through reduced equipment downtime and better overall comfort. One of the primary obstacles to the development of FDD systems for HVAC&R systems has been the lack of data to quantify these potential cost savings benefits. However, in comparison to chemical process plants, the cost savings are undoubtedly a smaller portion of the costs of operating the businesses that they serve. This means that FDD systems for non-critical HVAC&R applications must have lower installed costs to achieve the same cost-to-benefit ratio.

Clearly, achieving low installed costs is a critical factor in enabling the deployment of FDD systems in HVAC&R applications. Interest in FDD has grown as the costs of sensors and control hardware have gone down. In addition, there has been an emergence in the use of information technology within the HVAC&R industry for scheduling, parts tracking, billing, personnel management, etc. This has provided an infrastructure and higher expectation for the use of quantifiable information for better decision making. Finally, the structure of the industry that provides services for the operation and maintenance of buildings is changing. Companies are consolidating and offering whole building operation and maintenance packages. In addition, utilities are in the process of being deregulated and are beginning to offer new services, which could ultimately include complete facility management. The cost-to-benefit ratio for FDD improves as the industry moves towards large organizations managing the operations and maintenance of many buildings. In particular, the cost of developing and managing the necessary software tools can be spread out over a larger revenue base.

Chillers and other vapor compression equipment are excellent first applications for FDD within the HVAC&R industry. The total maintenance and operating costs for primary cooling equipment are significantly greater than those for auxiliary equipment used in cooling buildings. Furthermore, vapor compression technology is by far the most common type of primary cooling equipment in use. This paper provides an overview of FDD as applied to vapor compression equipment, including recent developments, future R&D needs, and commercial potential.

Service Tools versus Automated FDD

The first FDD systems that have appeared for HVAC&R applications are portable devices that are used by service technicians in the course of maintaining and servicing chillers or other vapor compression cooling equipment. During a “check up”, the technician connects sensors to the equipment and provides some general description of the equipment being monitored. The measurements are compared with generic expectations for the specific type of equipment so problems can be identified and diagnosed. Because of the generic nature of the methods embedded in these tools, only relatively large faults can be detected and diagnosed. Furthermore, problems are only detected and diagnosed after occupants have complained or during the course of a technicians regular maintenance schedule. However, a single FDD system can be used for many pieces of equipment, which improves the cost-to-benefit ratio and thereby allows the use of more expensive sensors. This is a logical initial deployment of FDD for the HVAC&R industry.

Some service tools for chillers employ vibration sensors to detect and diagnose mechanical problems, such as bad bearings that eventually could lead to failure. The technician records vibration signatures at regular maintenance intervals (e.g., 6 months) and the signatures are compared with expectations associated with normal behavior and specific faults. The expectations are typically expressed in terms of dominant frequencies for specific sensor locations and types of equipment. Significant changes in the frequency content can indicate specific mechanical problems.

More recently, some simpler and lower cost FDD service tools have been developed for vapor compression cooling equipment. These tools utilize temperature and pressure measurements, along with simple rules to detect and diagnose problems that impact the thermodynamic behavior of the system.   The faults include loss of refrigerant, loss of evaporator or condenser air/water flow or effectiveness (fan/pump, fouling, filter clogging), loss of refrigerant flow (filter drier, expansion device, or compressor), presence of non-condensables (air), and loss of compressor efficiency. The tools can be applied to identify problems that have led to a loss of comfort or as part of a regular maintenance schedule.

The functionality/benefits and costs of a fully automated FDD system differ significantly from those of a service tool. Figure 1 depicts a vision for automated FDD applied to a number of packaged air conditioners. FDD systems would be integrated into individual equipment controllers and would provide continuous monitoring, fault detection and diagnostic outputs, and recommendations for when service should be performed. Ultimately, the use of automated FDD systems could allow a small support staff to operate, monitor, and maintain a large number of different systems from a remote, centralized location. Local FDD systems would communicate across a network to provide a status report on the "health" of the equipment that they monitor. Failures that lead to loss of comfort could be identified quickly before there is a significant impact on comfort. In many cases, degradation faults could be identified well before they lead to loss of comfort or when they result in uneconomical operation, allowing more efficient scheduling (lower cost) of service.

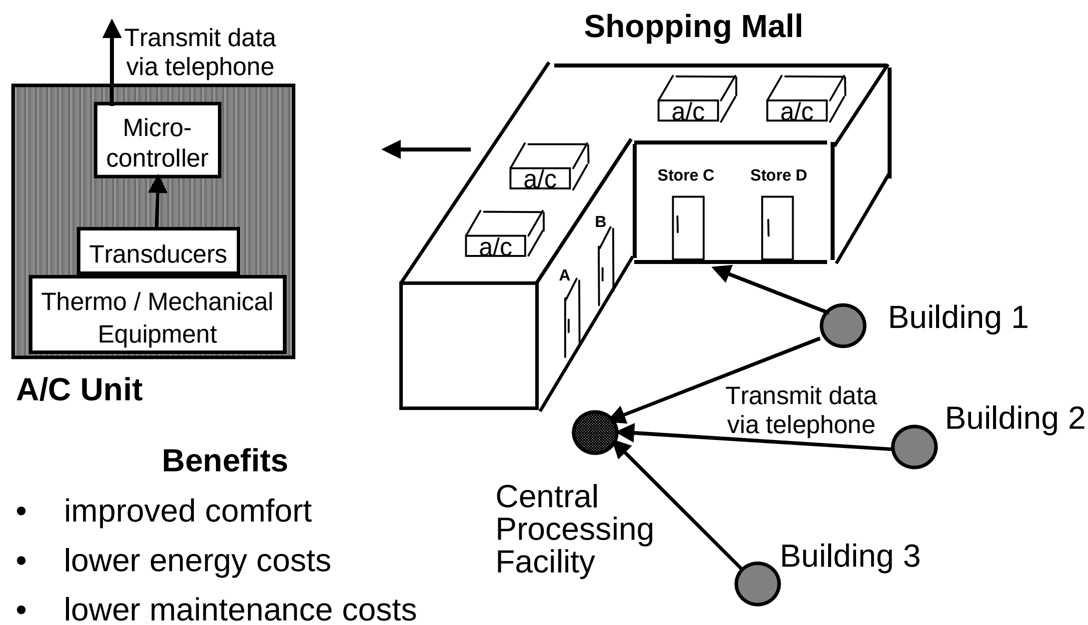

Figure 1. Vision for a fully automated FDD system

Automated FDD systems should provide lower service and operating costs plus improved comfort as compared with off-line service tools. However, the initial cost of each FDD system could not be spread out over a number of cooling systems and as a result, low cost sensors will be necessary. At present, no fully automated FDD systems have been integrated into individual controllers for HVAC&R equipment and are available as commercial products. In general, larger equipment applications (e.g., chillers) can absorb more add-on costs than smaller ones (e.g., rooftop units) and therefore automated FDD will probably appear first in larger equipment.

Elements of an Automated FDD System

Faults for vapor compression systems can be divided into two categories: 1) "hard" failures that occur abruptly and either cause the system to stop functioning or not meet comfort conditions and 2) "soft" faults that cause a degradation in performance but allow continued operation of the system. Many of the most frequently occurring and expensive faults are associated with service in response to hard failures, such as compressor and electrical faults. Certainly, an automated FDD system should be able to diagnose "hard" faults. However, these faults are typically easy to detect and diagnose using inexpensive measurements. For instance, a compressor failure leads to a complete loss of refrigerant flow and can be easily diagnosed by monitoring the temperatures or pressures at the inlet and outlet of the compressor. Similarly, a fan motor failure could be diagnosed by measuring temperatures or pressures at the inlets and outlets of the heat exchangers (evaporator or condenser) that they serve. Other hard faults that should probably be included within an FDD system include common controls failures, blown fuses, and malfunctioning electrical components such as contactors. It would also be important to detect dangerous operating conditions, such as the possibility of a flooded start, that lead to "hard" failures. "Soft" faults, such as a slow loss of refrigerant or fouling of a heat exchanger, are more difficult to detect and diagnose. Furthermore, they often lead to premature failure of components, a loss in comfort, or excessive energy consumption.

For faults that do not directly lead to an equipment shutdown, two primary modules should be utilized within an automated FDD system (see Figure 2): 1) a Fault Detection and Diagnostics (FDD) Module and 2) an Evaluator Module. The FDD Module utilizes measurements from the system to detect and diagnose problems as they occur. Typically, it is possible to identify many minor problems (e.g., heat exchanger fouling) before they significantly impact the performance of the system in terms of either cooling capacity of efficiency. Therefore, after faults are identified, the Evaluator Module must determine whether they are significant enough to warrant service. The outputs of the Evaluator Module could be recommendations that include: do nothing, adjust the control to compensate for the fault, schedule service when it is convenient, or shut the unit down and repair now.

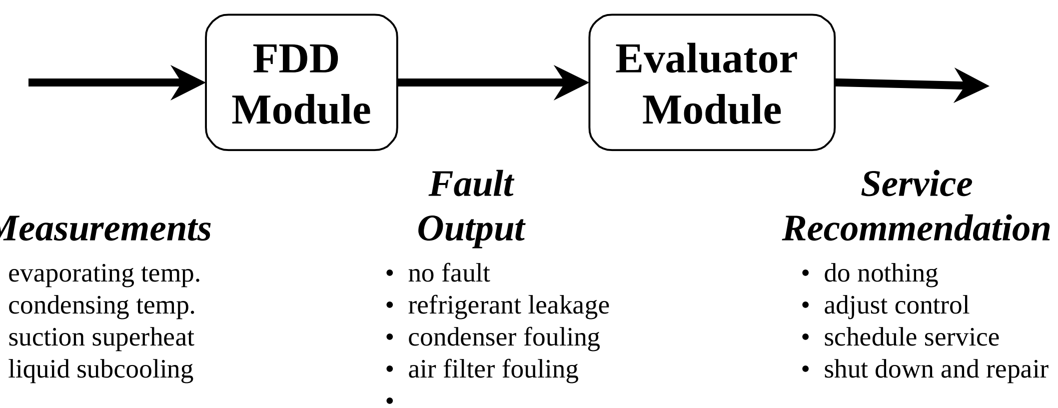

Figure 2. Software elements of an FDD system

FDD Module

FDD methods have only recently been investigated for vapor compression cooling equipment. Contributions have been made by McKellar (1987), Stallard (1989), Yoshimua and Noboru (1989), Kumamaru et al. (1991), Wagner and Shoureshi (1992), Hiroshi et al. (1992), Grimmelius et al. (1995), Gordon and Ng (1995), Rossi and Braun (1996), Stylianou and Nikanpour (1996), Peitsman and Bakker (1996), Stylinaou (1997), Rossi and Braun (1997), Breuker and Braun (1998a, 1998b), and Baily (1998). For the most part, FDD methods that have been developed use thermodynamic measurements to detect and diagnosis common faults that degrade system cooling capacity and efficiency and impact the life of equipment. The use of temperature measurements is appealing because of the relatively low cost requirements for this application. The faults considered include compressor valve leakage, heat exchanger fan failures, evaporator frosting, condenser fouling, evaporator air filter fouling, liquid line restrictions, and refrigerant leakage. Of these studies, only Grimmelius et al. (1995), Stylianou (1997), and Baily (1998) investigated FDD methods for chillers.

The use of thermodynamic impact to detect and diagnose faults will be illustrated through the use of an example. Consider a packaged air conditioner with a fixed orifice as the expansion device, a reciprocating compressor with on/off control, fixed condenser and evaporator air flows, and R22 as the refrigerant. Figure 3 shows P-h diagrams for three cases of steady-state operation at a given set of secondary fluid inlet conditions to the evaporator and condenser: normal, fouled condenser, and low refrigerant charge. Condenser fouling is equivalent to having a smaller condenser and leads to higher condensing temperatures and pressures than for the normal (no fault) case. For a system with a fixed orifice, the higher condensing pressures lead to a greater condenser to evaporator pressure differential which tends to increase the refrigerant flow rate. Furthermore, the increased flow rate tends to reduce the amount of condenser subcooling and evaporator superheat and increase the evaporating temperature. In contrast, the loss of refrigerant tends to lower the pressure throughout the system leading to reductions in both evaporating and condensing temperatures. The lower evaporating pressure and corresponding vapor density leads to a lower refrigerant flow rate which results in higher evaporator superheat and a higher refrigerant discharge temperature from the compressor. This example illustrates that condenser fouling and low refrigerant can be distinguished by their unique effects on thermodynamic measurements.

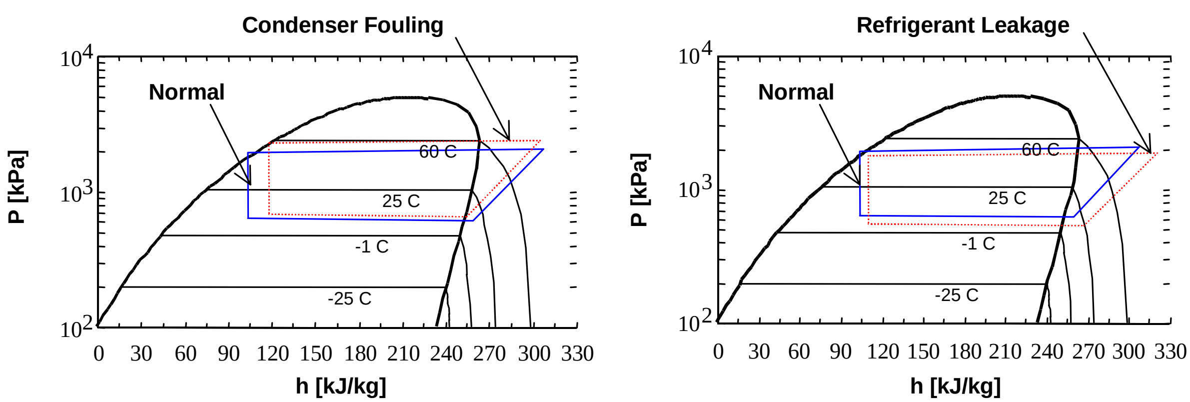

Figure 3. Effect of faults on thermodynamic states

Most of the proposed FDD methods for cooling equipment use differences between measurements and expectations of thermodynamic states at steady state for detection and diagnoses of faults. Expected values for thermodynamic states under normal operation depend upon ambient and room conditions. Figure 4 shows the structure of the FDD technique developed by Rossi and Braun (1997) for rooftop air conditioners. At most, nine temperatures and one relative humidity are required. Three of the measurements are used to characterize the inputs (**U**) that affect the operating states of the unit: the temperature of the ambient air into the condenser coil (T_{amb}), the temperature of the return air into the evaporator coil (T_{ra}), and the relative humidity (Φ_{ra}) or wet-bulb temperature (T_{wb}) of the return air into the evaporator coil. In a normally operating, simple rooftop air conditioning unit (on/off compressor control, fixed speed fans), all the output states (**Y**) in the system are assumed to be functions of only these three driving conditions. The output state measurements used by the technique are: 1) evaporating temperature (T_{evap}), 2) suction line superheat (T_{sh}), 3) condensing temperature (T_{cond}), 4) liquid line subcooling (T_{sc}), 5) hot gas line or compressor outlet temperature (T_{hg}), 6) air temperature rise across the condenser (ΔT_{ca}), and 7) air temperature drop across the evaporator (ΔT_{ea}). A steady-state model is used to describe the relationship between the driving conditions and the expected output states in a normally operating system. Residuals (**ΔY**) are formed as the difference between the measured output states ($\mathbf{Y_{meas}}$) and those predicted by the steady-state model ($\mathbf{Y_{exp}}$). The residuals are used by the detection classifier to determine a binary "fault" or "no-fault" output and by the diagnostic classifier to identify the most likely cause of the faulty behavior.

A rooftop unit typically utilizes "on/off" control and spends a significant amount of time in a transient condition. When a steady-state model is used to predict normal operating states, a steady-state detector must be used to distinguish between transient and steady-state operation. The steady-state detection classifier provides a binary output that is an input to a switch (SW) that controls the output of the FDD system. The FDD system will only indicate a fault and provide a diagnosis when the system is in steady state.

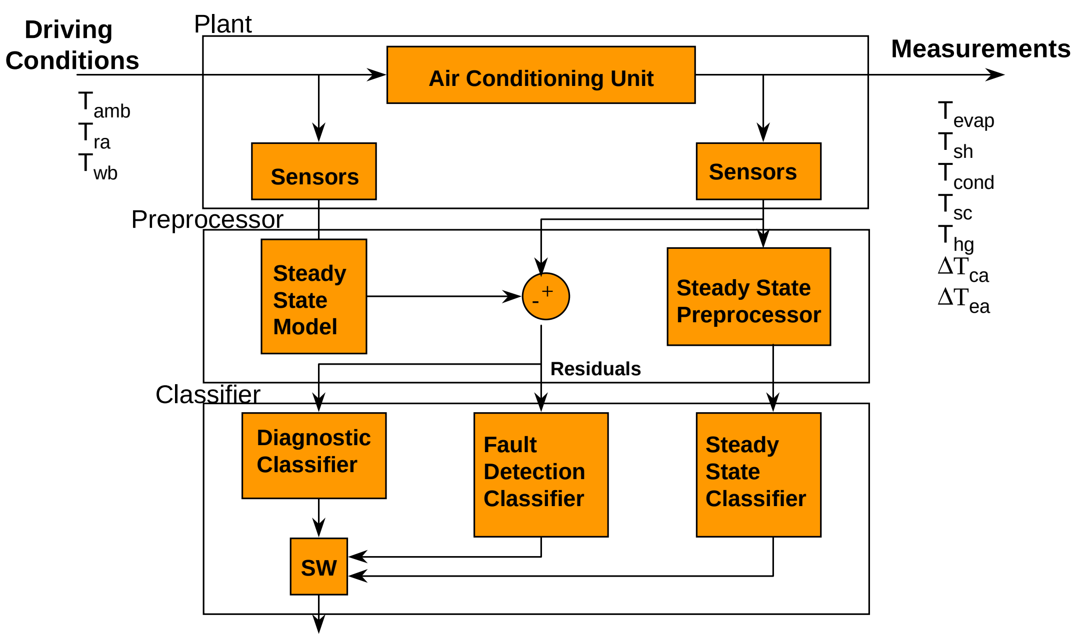

Figure 4. FDD Approach of Rossi and Braun (1997)

The fault detection classifier of Rossi and Braun (1997) estimates the probability that the current behavior is normal. A fault is indicated when the probability falls below a threshold, termed the fault detection threshold. Fault diagnosis is performed using a statistical, rule-based classifier. The set of rules relates each fault to the direction that each measurement changes when the fault occurs. Table 1 gives the diagnostic rules for the five faults and seven output measurements developed by Breuker and Braun (1998). The arrows in Table 1 indicate whether a particular measurement increases (↑) or decreases (↓) in response to a particular fault at steady-state conditions. For instance, as previously shown, the loss of refrigerant generally causes the superheat of the refrigerant entering the compressor to increase above its “normal” value at any steady-state condition. Each of the faults results in a different combination of increasing or decreasing measurements with respect to their normal values. The rules of Table 1 are effectively fault models that are generic for this type of air conditioner. The diagnostic classifier evaluates the probability that each fault applies to the current operation.

Table 1. Rules for the diagnostic classifier

Fault	T_{evap}	T_{sh}	T_{cond}	T_{sc}	T_{hg}	ΔT_{ca}	ΔT_{ea}
Refrigerant Leak	↓	↑	↓	↓	↑	↓	↓
Compressor Valve Leakage	↑	↓	↓	↓	↑	↓	↓
Liquid-Line Restriction	↓	↑	↓	↑	↑	↓	↓
Condenser Fouling	↑	↓	↑	↓	↑	↑	↓
Evaporator Fouling	↓	↓	↓	↓	↓	↓	↑

Breuker and Braun (1998b) did extensive experimental evaluations of the performance of the FDD technique developed by Rossi and Braun (1997). Steady-state and transient tests were performed on a simple rooftop air conditioner in a laboratory over a range of conditions and fault levels. The data without faults were used to train the models for normal operation and determine statistical thresholds for fault detection, while the transient data with faults were used to evaluate FDD performance. Table 2 shows results that characterize the sensitivity of the FDD method for detecting and diagnosing faults. The level at which each fault could be detected at one point ("First Detected") and at all steady-state points ("All Detected") from the database of transient test results are presented for the five faults along with the corresponding percent loss in capacity and COP and the change in superheat and subcooling at these detectable levels. These results show that the faults can generally be detected and diagnosed before a decrease in capacity or efficiency of 5% is reached. In terms of the effect on performance, the technique is less sensitive to compressor valve leakage and evaporator fouling. At these levels, the changes in compressor superheat and hot gas temperature were probably not large enough to impact the life of the compressor.

Table 2. Performance of FDD Prototype (3 input, 10 output temperatures)

Performance Index	Refrigerant Leakage (% Leakage)		Liquid Line Restriction (% ΔP)		Compressor Valve Leak (% $\Delta\eta_v$)		Condenser Fouling (% lost area)		Evaporator Fouling (% lost flow)	
	1st	All	1st	All	1st	All	1st	All	1st	All
Fault Level (%)	5.4	Max	2.1	4.1	3.6	7.0	11.2	17.4	9.7	20.3
% Loss Capacity	3.4	> 8	1.8	3.4	3.7	7.3	2.5	3.5	5.4	11.5
% Loss COP	2.8	> 4.6	1.3	2.5	3.9	7.9	3.4	5.1	4.9	10.3
ΔT_{sh}	5.4	> 11	2.3	4.8	-1.8	-3.6	-0.6	-1.6	-1.7	-2.7
ΔT_{hg}	4.8	> 10	2.4	4.8	0.0	0.0	1.8	2.3	-1.2	-2.7

Evaluator Module

The results of Table 2 indicate that an FDD technique can be designed to detect and diagnose faults well before there would be a need to repair the unit. Thus, an FDD system should evaluate the impact of the fault before recommending a course of action. These recommendations should be based upon the severity of the fault with respect to four criteria: 1) impact on equipment safety, 2) environmental impact, 3) loss of comfort, and 4) economics.

Equipment safety primarily relates to the compressor and motor. The compressor/motor should not operate under conditions that will lead it to fail prematurely. These conditions include liquid entering the compressor, high compressor superheat, high pressure ratio, high discharge pressure, high motor temperatures, low oil, etc. Existing controllers generally have safeties that will shut the unit down in the event of operation at adverse conditions. Under these circumstances, the FDD system could add an explanation regarding the probable fault that led to the shutdown. In addition, lower level warning limits should be established for these variables. When these limits are exceeded, the Evaluator might recommend that service be performed when convenient.

The environmental criterion primarily relates to refrigerant leakage. Refrigerant leakage is an environmental hazard and should be repaired quickly. This is particularly true if the refrigerant is toxic (ammonia). However, when a refrigerant leak is detected and diagnosed, the actual output of the Evaluator might depend upon the rate of refrigerant leakage and type of refrigerant. For a small leak, it may be acceptable to keep the unit running and schedule repairs for the near future. Conversely, for a large leak, it may appropriate to shut the unit down and call for immediate repairs.

Ideally, the Evaluator should be able to identify if the current “health” of the equipment is such that it, in the future, it will not have sufficient cooling capacity to maintain comfort. Once a fault has been identified, then this feature would allow scheduling of service to address this need rather than requiring immediate service in response to a loss of comfort (i.e., complaints). This could involve the use of on-line models for predicting cooling capacity and cooling needs.

If a fault has been identified, but the current operation is not adversely affecting the equipment life or the environment and the system can maintain comfort both now and in the future, then service should be performed only if it is economical to do so. In this case, the best decision results from a tradeoff between service and energy costs. Service costs money but reduces energy costs. Rossi and Braun (1996) developed a simple method for optimal maintenance scheduling for cleaning of heat exchangers and replacing air-side filters. The method relies on measurements of power consumption, estimates of cost per service, and utility rates, but does not require any forecasting. They estimated total cost savings between 5 and 15% for optimal versus regular maintenance scheduling.

R&D Needs

Although the technology and incentives for application of FDD systems for vapor compression cooling equipment have never been greater, there still are several obstacles to their development and deployment. First of all, there is a need to quantify the potential benefits in order to establish benchmarks for acceptable costs and to provide marketing information. Specific research issues related to FDD methods include development of methods for detection and diagnosis of sensor and multiple simultaneous faults, identification of appropriate models and training approaches, and evaluation of the tradeoffs between sensors (type and quality) and FDD performance. The testing of FDD methods should be performed first in the laboratory and then in the field.

Commercial Potential

Chillers will probably be the first application of automated FDD within the HVAC&R industry because of a low cost-to-benefit ratio. Once fully developed, the technology could be integrated into all controllers associated with vapor compression cooling equipment. When fully mature, the costs associated with implementing the technology should be primarily due to the addition of low cost temperature sensors. These costs should be a relatively small fraction of the controller costs. The same technology would also be applicable to refrigeration and residential space cooling. Furthermore, the technology could be implemented in add-on systems to existing cooling equipment, which would increase the rate of market penetration. Automated FDD is coming for vapor compression cooling technology. It's just a matter of time.

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